Some Problems of Long-distance Radio-telegraphy.[1]

By Dr. J. A. Fleming, F.R.S.

I.

THE achievement of transatlantic radio-telegraphy in 1901 and 1902 was of interest to physicists chiefly by reason of the fact that they did not see clearly why it should have been possible at all. The mystery of it was increased when at later dates radio signals were transmitted a quarter of the way round the world, and finally, with high-power stations and thermionic valves detected even at the Antipodes.

The wave-length of the waves used in the earliest work at Poldhu was about 3000 ft. The earth, roughly speaking, is a sphere 42 million feet in diameter. Hence the ratio of wave-length then used to earth diameter was about 1 : 14,000.

In the case of light there is a small bending or diffraction of the wave round an opaque obstacle. In other words, there is some small amount of illumination within the boundary of the geometrical shadow. The average wave-length of light waves is about 1/2000th of a millimetre, and a sphere having a diameter of 7 mm. would be 14,000 of such wave-lengths. Now if an exceedingly small source of light were placed on the pole of a sphere 7 mm. in diameter in a dark region, it is certain that there would be no illumination at the equator of the sphere. In other words, there would not be any sensible diffraction at an angular distance of 90°. Modern long-distance radio-telegraphy conducted with waves of wave-length approximating to 10 miles or so can communicate even with the Antipodes.

The mathematical treatment of the problem of the diffraction round a conducting sphere of electric waves which are radiated from a transmitter at its pole consists in expressing the magnetic and electric forces at any angular distance θ in the form of a series of harmonic terms. It is in the summation of this series to obtain the integral effect at the receiver that the chief difficulties and differences of opinion occur, and most analysts have employed only an approximation. In 1918 Prof. G. N. Watson effected a new and complete summation which enables the value of the forces to be calculated for any point on an imperfectly conducting sphere.

The result of eighteen years' work on this problem by mathematicians of the highest rank has been to give us a formula for the current in a receiving aerial of given resistance determined in terms of wave-length, aerial heights, and distance which represents the result of pure diffraction acting round a spherical earth of perfect conductivity. On the other hand, when we come to compare the results of this diffraction formula with actual observations in practice we find an enormous discrepancy. The actual received currents in the case of long-distance stations for the usual sending aerial currents are hundreds of thousands, or even millions, of times greater than the received current predicted by the theoretical formula. Thus, to take a case quoted by Dr. Van der Pol from observations made at Darien Radio Station, on the Panama Canal, on radio signals sent from Nauen, near Berlin, Dr. L. W. Austin gives the following figures: $I_1 = 150$ amperes, $\lambda = 9{\cdot}4$ km., $a_1 h_1 = 120$ metres, $a_2 h_2 = 146$ metres, $R_2 = 29$ ohms, and $d = 9400$ km. Now the actual received current was $I_2 = 1{\cdot}3$ microamperes, but the value predetermined by the formula is only 0·6 of one millionth of a microampere. In other words, the actual received current in this case is two million times greater than the predicted current.

The upshot of the whole matter then is this: Long-distance radio-telegraphy, say, round one-quarter of the circumference of the earth, would certainly be quite impossible but for some cause, other than diffraction, operating to compel the waves to follow round the earth's curvature and not quickly glide off it.

Oliver Heaviside in 1900 suggested that an upper conductive layer on the atmosphere might act as a guide to the waves, radio-telegraphy being, in fact, conducted in a thin spherical shell of non-conductive air bounded by a conductive earth and a conductive upper air. He did not furnish any valid reasons to explain why this upper air conducts and how its conductivity is preserved, and although the suggestion has been very generally accepted by radio engineers, it has been taken without sufficient criticism of its difficulties and details. There has been in the intervening twenty-one years an immense accumulation of facts, all showing, however, that long-distance radio-telegraphy is conditioned by the physical constitution of our atmosphere and is very far removed indeed from being simple electromagnetic wave propagation in empty space. An important epoch in this connection is the year 1902, when Senatore Marconi discovered during one of his early voyages across the Atlantic in the s.s. *Philadelphia* in February, 1902, that radio signals from Poldhu could be received at night about thrice the distance they could be read in daytime, being detectable only up to 700 miles by day, but readable up to 2099 miles by night.

It was at once surmised that the difference was due to ionisation of the air by sunlight, which, by liberating electrons from atoms, gives to the air conductivity. It was some years before this vague suggestion was converted by Dr. W. H. Eccles into a more definite scientific theory, many speculations in the meantime being found wanting in adequate basis, such as that which regarded the sunlit air as having an absorption for the energy of electromagnetic waves similar to that of foggy or misty air for visible light.

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[1] Abridged from two sections of the Trueman Wood lecture on "The Coming of Age of Long-distance Radio-telegraphy and Some of its Scientific Problems," delivered before the Royal Society of Arts on November 23, 1921. The complete lecture is published in the Journal of the Society for December 9 and 16, 1921.

Before entering into further discussions of the facts, it will be convenient to mention a few of the generally accepted views as to the constitution of the terrestrial atmosphere and its ionisation by light.

By the use of hydrogen-filled sounding balloons carrying self-recording meteorographs, it has been possible to explore the atmosphere up to a height of about twenty miles. One of the results is to show that our atmosphere may roughly be divided into two regions. In the lower layer, called the *troposphere*, the atmospheric gases are kept well mixed up by winds and convection. This layer extends to a height of six or seven miles or so, and in it the temperature falls regularly with increasing height at the rate of about 6° C. per kilometre of ascent until a temperature of about − 55° C. is reached. Above this is a zone called the *stratosphere*, of unknown thickness, in which the temperature remains constant. Above a height of about seven miles water vapour is absent, and at higher levels convection ceases to operate and the atmospheric gases arrange themselves in order of density. The outer and highest levels above a height of sixty miles (= 100 km.) are chiefly composed of helium and hydrogen with possibly some small admixture of the rarer atmospheric gases neon and krypton.

The volume composition of the atmosphere at the earth's surface is as follows :—

Nitrogen ...	78·05 per cent.
Oxygen ...	21·00 „
Argon ...	0·93 „
Carbon dioxide	0·03 „
Hydrogen ...	1 to 10 vols. in a million of air.
Neon... ...	10 „ „
Helium ...	1 to 2 „ „
Krypton ...	1 vol. „ „
Xenon ...	0·05 „ „ „

Oxygen is almost entirely absent at a height of 100 km., but nitrogen is still present in a rarefied form. The presence of hydrogen and helium at these high levels has been indicated by an observation of Pickering on the spectrum of a meteoric stone entering the earth's atmosphere, which showed the hydrogen and helium lines.

Next, as regards the action of light on the gases of the atmosphere. Light waves of high refrangibility impinging on nearly all substances, especially those containing electropositive atoms, liberate from them electrons. The atom is now considered to be a collocation of negative electrons arranged in concentric shells, possibly in orbital motion, round a central positively charged nucleus in which the gravitative mass of the atom chiefly resides. Light of short wave-length causes one or more of these negative electrons to be detached and projected with a high velocity. The more electronegative an atom is the higher must be the frequency of the light to affect it. The electrons so detached are called photo-electrons and the action photo-electric.

In the case of sodium or potassium, which are highly electropositive metals, photo-electrons are emitted under the action of visible light, about the middle of the spectrum, but for less electropositive metals—*e.g.* zinc and magnesium—the action takes place only with ultra-violet light. Hence it follows that a plate of zinc illuminated by light from an electric arc or by the spark between aluminium balls loses a negative charge readily, and if insulated, becomes positively electrified owing to the loss of negative photo-electrons. The velocity with which these photo-electrons are projected is considerable, and may be 500–1000 km. per sec.

For most metals the ionising potential is about two to four volts, hence the maximum wave-length of ionising light is just beyond the violet end of the visible spectrum. But for atmospheric gases, when pure and free from dust or moisture, the ionising potential is much higher, being approximately as follows :—

Nitrogen ...	7·5 volts	Argon ...	12 volts
Oxygen ...	9 „	Neon ...	16 „
Hydrogen ...	11 „	Helium ...	20·5 „

It follows from this that the atmospheric gases cannot be ionised by light of longer wave-length than 1350 Å.U. Rays of this short wave-length are not transmitted by quartz but only by certain samples of fluorite, and are absorbed by a very small thickness of air. No sunlight of shorter wave-length than about 2950 Å.U. reaches the earth's surface, as shown long ago by Huggins and Cornu.

Hence the conclusion is forced on us that pure dust-free atmospheric gases cannot be ionised at the lower levels of the atmosphere by the direct action of sunlight, but at the higher levels above 60 to 100 km. doubtless there is direct ionisation.

Nevertheless, ionisation does take place in the lower atmospheric levels, as shown by the small finite electric conductivity possessed by the air, which proves that there are negative ions, either free electrons, or electrons attached to neutral atoms, and also positive ions present in the air, even over wide oceans. Thus, Boltzmann found in tests made in mid-Atlantic 1150 positive and 800 negative ions per c.c. of air. A. S. Eve found 600 to 1400 positive and 500 to 1000 negative ions per c.c., the positive being slightly in excess.

This ionisation may be produced either by photo-electric action on dust or ice particles in the air, by radio-active matter in the soil, by photo-electric action upon complex gaseous molecules in the air, or generated by the light and called condensation nuclei. Such agencies, however, cannot account for the far larger and permanent ionisation necessary to give the required electric conductivity in the higher atmosphere if it is to act as a guide to long electromagnetic waves.

A consideration of the terrestrial radio-telegraph problem shows that if there is any conductive layer in the upper atmosphere which can act as a guide to long electromagnetic waves round the earth, it must possess the following properties :—

(1) It must be permanently ionised, which means that its ionisation must not vanish in the night-time since, so far as we know, its guiding powers are not suspended on the shadow side of the earth. This seems to imply that the ionisation must be predominantly of one sign or that the *plus* and

minus ions are so far separated that they do not readily recombine. True gaseous photo-ionisation always produces ions of both signs in equal number mixed up together, and the conductivity quickly disappears when the ionising agency is withdrawn.

(2) The resulting electric conductivity must be sufficiently high, say, as good as that of ordinary fresh water, to act as a true wave guide. This implies that the ions must be very numerous per c.c. and very mobile or have high ionic velocities under unit electric force.

Bearing in mind that the upper regions of the earth's atmosphere above the 100 km. level probably consist chiefly of hydrogen, and that the velocity of ions in hydrogen under unit electric force is, according to measurements, from two to three times that in oxygen or nitrogen at the same pressure, it is easily seen that in the upper hydrogen levels of the atmosphere a very moderate amount of ionisation, say, 10^7 ions per c.c., might give a conductivity of the order of that of fresh water, or about 700,000 ohms per c.c. Another quality this conducting layer must possess if it is to act as a true reflector of long waves is a somewhat sharply defined lower surface.

It has already been remarked that observations on signal strength over long distances show an enormous difference between the actual measured values and those predicted by a simple diffraction formula. Attempts have been made to find an empirical formula for the received current in terms of the other quantities involved. At first these efforts started with the erroneous assumption that the attenuation might be regarded as due to an "absorption" caused by the atmosphere, and therefore mathematically represented by an exponential factor appended to the simple Hertzian expression for the magnetic or electric force at a known distance on the equatorial plane of a small oscillator.

Prof. G. N. Watson finds that if in place of a perfectly conducting spherical earth in free space we assume an earth having a conductivity about the same as sea water, enclosed in a spherical sheath or shell of material having a conductivity of about $1{\cdot}44 \times 10^{-15}$ E.M.U., equal to a specific resistance of 700,000 ohms per c.c. or not far from that of ordinary fresh water, the interspace being about 100 km., then the diffraction formula for the receiving aerial current would have to be modified and the exponential factor becomes $\epsilon^{-9{\cdot}6\theta/\sqrt{\lambda}}$. Watson therefore considers that if we are able to assume an upper conducting layer in the atmosphere at a height of about 100 km. having a fairly sharp under-surface and a specific resistance of about 700,000 ohms or, say, 0·75 megohm per c.c., then guided wave propagation through the included spherical shell of insulating air would account for the observed attenuation in actual terrestrial long-distance radio-telegraphy.

We have then to consider what are the probabilities and possibilities for the existence at a height of 100 km. or so of such a conducting layer and how it may be supposed to become ionised. Gaseous conductivity is always and only due to the presence of ions, and in the above case these are created by the strong electromotive forces brought into play. In gases contained in glass vessels there are always some few free ions or electrons present for some reason. If a high frequency magnetic field is made to act on the gas these ions are driven with great force against the gas molecules and ionise them, thus producing very quickly a copious supply of ions and giving the gas high conductivity. We cannot, however, say that a rarefied gas is a good conductor *per se* for very feeble impressed electromotive forces as we can say that a metal is a good conductor. Hence mere rarefaction due to height will not bestow the required electric conductivity on the atmosphere. Neither can the required ionisation be produced by solar light, because then it would vanish in the night-time by recombination of the ions.

The suggestion I wish to make as to the cause of this ionisation is based upon a modification of hypotheses already advanced by S. Arrhenius, K. Birkeland, and W. J. Humphreys concerning the projection of dust by light pressure from the sun.

We know that the sun's photosphere is in a continual state of disturbance due no doubt to violent explosions in regions beneath this light-giving locality. Above this photosphere lies the so-called reversing layer composed of metallic vapours which produce the Fraunhofer lines in the spectrum. These eruptions carry up not only metallic vapours, but also vast masses of the superlying chromosphere composed chiefly of hydrogen and helium gases in the form of solar prominences or red flames which are often seen rising to a height of several hundred thousand kilometres in a few minutes, thus indicating velocities of several hundred kilometres per second. When these solar metallic vapours are thus carried up into colder regions they must be condensed into a metallic mist or rain composed of particles of various sizes. We know also from experiment as well as theory that light exercises a pressure on solid objects and that this pressure per square centimetre for totally absorbing or black bodies is numerically equal to the light energy in the cubic centimetre. Measurements made of the so-called solar constant at the earth's surface when corrected for atmospheric absorption give a value of 2·5 gram calories per sq. cm. per min. Hence the energy of light per c.c. is nearly $6/10^5$ ergs and the light pressure therefore $6/10^5$ dynes per sq. cm. on a black surface. But at the sun's surface this pressure is 46,000 times greater, or 2·75 dynes per sq. cm. As this pressure varies as the square of the linear dimensions of the particle whilst gravitation varies as the cube, it is clear that as the dimensions of a particle decrease a limit will be reached at which the light pressure will overbalance the gravitation attraction.

It is easy to prove from known data that at or near the sun's surfaces black particles of the density of water would be just repelled if they had diameters of 15,000 Å.U. $= 150/10^6$ cm.

If their density is 5·5, then the critical diameter will be 2700 Å.U. If, however, the particles have diameters of only 1600 Å.U. and unit density the light pressure will be nineteen times greater than the gravitation attraction. For sizes still smaller the light pressure would decrease again, and for diameters less than 500 Å.U. gravity would once more preponderate.

If, then, the solar eruptions drive up into colder regions vapours which are condensed to liquid or solid particles, a sorting action will at once come into play. Particles above a certain diameter will be drawn back into the sun. Particles below a certain diameter will be repelled away with great force by light pressure, and particles of a certain critical diameter will remain suspended in space. The solar corona may perhaps be in part composed of solar dust of this critical diameter, as Arrhenius has suggested. Now, as regards that dust which is repelled by the sun, it is easy to calculate the time particles of certain sizes will take to travel to the earth's orbit and the velocities they will then possess. Taking the particles to have unit density and three sizes, viz. 1600, 5000, and 10,000 Å.U., and to be projected from the sun with velocities of 200 km. per sec., I find that the times required to travel to the earth's orbit will be respectively twenty-two hours, forty-two hours, and seventy-six hours. The velocities with which they will arrive will be 1700 km. per sec., 780 km. per sec., and 350 km. per sec. respectively.

These minute particles, composed, it may be, of carbon from the photosphere or metallic dust from the reversing layer or volcanic ash or other solar materials will in general carry electric charges. The high temperature will cause emission of electrons from the metallic particles, as also will the fierce ultra-violet radiation to which they are exposed. The metallic vapours will also be in a state of ionisation, and the free electrons emitted will condense round them gases or vapours from the chromosphere as they pass through it. Hence the particles which are repelled by light may be either positively or negatively electrified or neutral. Owing to the greater tendency of negative electrons to condense vapours and attach themselves to groups of molecules, the negatively charged particles may be less dense and smaller than those positively charged. It should be noted, however, that isolated molecules or electrons are far too small in diameter to be repelled by light. It is only groups of molecules of at least 500 Å.U. in diameter which can be repelled. Hence these dust particles will travel outwards from the sun with very different velocities. Some will come with great velocity and others with small speed.

In short, we may say that the sun, like a good housemaid, dislikes dust, especially dust of a certain degree of fineness, and pushes it away from it with great force. The moment that this electrified dust enters the earth's magnetic field with high velocity forces will be brought to bear on it tending to separate the negatively and the positively charged particles. If H is the magnetic force of the earth and v the particle's velocity, and e its charge, then the separating force is Hev where H is that component of magnetic force at right angles to the direction of v and the separating force is also at right angles to the plane of H and v.

(*To be continued.*)

Obituary.

Sir Ernest Shackleton, C.V.O.

THE sudden death of Sir Ernest Shackleton on board the *Quest* at South Georgia on January 5 stopped the career of the most brilliant of Antarctic explorers just on the threshold of the South Polar regions which he was entering for the fifth time with his third expedition. That such a courageous and indomitable explorer should die a natural death after a lifetime of hair-breadth escapes from perils of ice, of starvation, of shipwreck, and of war is a grim stroke of Nature's irony. Great as his loss is to geographical exploration, we cannot but recognise his end as happy, for his life was arrested in the full course of the enthusiastic pursuit of a great and crowning adventure. The sympathy of all who appreciate high-hearted deeds will flow towards his wife, to whose co-operation much of his success was due; towards his shipmates, who have nobly resolved to carry on the voyage; and towards Mr. John Q. Rowett, whose friendship for Shackleton made him undertake the main financial burden of the expedition.

Ernest Henry Shackleton was born at Kilkee, in Ireland, in 1874, removed to London with his father while still a schoolboy, and at an early age insisted on going to sea instead of following his father's profession of medicine. After voyages to South America and other parts of the world, he entered the service of the Union Castle Co., where he was during the stirring days of the Boer War. He had become an officer of the Royal Naval Reserve before the plans of the Antarctic expedition on the *Discovery* fired him with the desire for exploration. His application for a post on the expedition was refused, persisted in, and finally accepted, and he had a strenuous time on board as junior watch-keeping officer. The expedition sailed in August, 1901, and from the outset Shackleton was eager to undertake every piece of voluntary work. He assisted in the chemical and oceanographical observations, assumed the editorship of the *South Polar Times*, and read up the history of polar exploration. When Capt. Scott was making up his party for the great southern journey of 1902–3 he included Shackleton, who thus took part in establishing the "farthest south" of lat. 82° 17′ S., and saw the great range of mountains bordering the Ice Barrier on the west and stretching far to the southward. On the return journey Shackleton broke down from an illness which was probably scurvy, but he struggled on to